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13. ABSTRACT (*Maximum 200 words*)

This report discusses the work performed by the U.S. Army Research Laboratory (ARL) (formerly the Ballistic Research Laboratory [BRL]) to determine the impact of large caliber weapon recoil effects on lightweight combat vehicles. The work was motivated by concerns that the firing of such weapons could overturn the vehicle under certain conditions. A detailed engineering model/simulation of the vehicle was used to investigate the recoil dynamics for both stationary and fire-on-the-move scenarios.

The stationary scenarios consisted of canting the vehicle at various angles up to −10° with different weapon-to-hull offsets. Weapon firings were simulated with hull pitch and roll motions monitored. For the fire-on-the-move conditions, the vehicle was set at a nominal speed and micro-terrain profiles simulated a cross-country environment. By elevating the terrain profile under one side of the vehicle, the cant of 0° or −10° was achieved.

Time history examples, as well as statistical data for three different weapon systems, are presented. The major result of the analysis was that while there exists significant hull motion due to recoil, a catastrophic event (light armored vehicle [LAV] overturning) should not occur.

14. SUBJECT TERMS
recoil effects, LAV-105, canted vehicle, weapon effects, combat vehicles, recoil, gun tube

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1. INTRODUCTION

The United States Marine Corps (USMC) was concerned that the 105-mm gun recoil could have an adverse effect on their Light Armored Vehicle (LAV). It was their concern that various vehicle cant angles, combined with weapon-to-hull offsets, and/or vehicle motions could cause the vehicle to overturn. This effect is obviously undesirable in real world situations. The USMC expressed these concerns to the Army Materiel Systems Analysis Activity (AMSAA), which requested that the Ballistic Research Laboratory[1] (BRL) investigate the potential problem. A computer simulation study was performed by the BRL to determine the outcome of various firing and nonfiring scenarios.

The USMC LAV, with a crew of three, is essentially a new two-man turret (weighing 3,697 kg), installed on an upgraded 8 x 8 chassis. The chassis is very similar to the standard LAV, but contains additional buoyancy aids. Figure 1 is an artist's impression of the LAV fitted with a 105-mm rifled tank gun.

2. MODEL

The engineering simulation HITPRO (hit probability) contains detailed models of the subsystems found on the HIMAG (high mobility agility) test bed weapon system. Using HITPRO as a base, unique LAV components were integrated into the basic simulation in order to simulate the USMC LAV. All of the models' subroutines were used in the analysis, however, only a description of the main subroutines relative to this study follow. (See HITPRO User's Manual[2] for more detail.)

• *Hull Motion Generation*: In general, the hull is flexibly suspended over two moving tracks which are driven over a specified terrain. The hull has 5° of freedom with respect to the track, the tracks have 3° of freedom with respect to the earth, and the hull has 6° of freedom with respect to the earth. All of these calculations are performed in the hull motion section of the program.

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[1] The U.S. Army Ballistic Laboratory was deactivated on 30 September 1992 and subsequently became a part of the U.S. Army Research Laboratory (ARL) on 1 October 1992.

[2] Cushman, P. G., R. R. Dutcher, G. J. Grachis, and P. J. Kester. "HITPRO III Computer Model Volume II, Model Development," Special Publication: ARLCD-SP-81007, prepared by General Electric Company, Pittsfield, MA, prepared for: U.S. Armament Research and Development Command, Dover, NJ, November 1981.

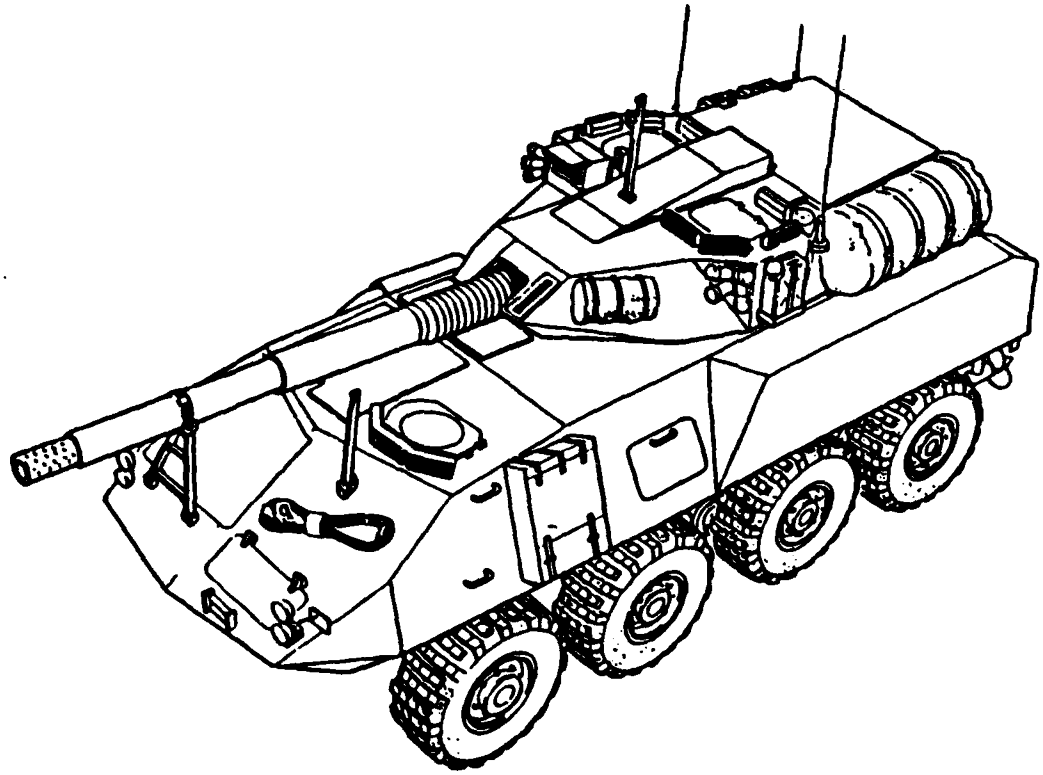

Figure 1. Light armored vehicle.

• *Cant of the Vehicle*: To produce a canted vehicle, a specific terrain profile needed to be chosen. The cant of a vehicle actually occurred by canting the terrain and having the vehicle move onto this terrain. This condition was achieved by adding one-half the total desired cant to the right track terrain data, and subtracting one-half the total desired cant angle from the left track terrain data. After a few seconds of motion onto the canted terrain, the vehicle became properly canted.

• *Chassis/Suspension*: The chassis/suspension model utilized in this simulation generated vertical wheel motions. The position and velocity of each road wheel determine how the suspension forces and torques are exerted on the hull. These flexible motions were calculated from various components including terrain data, vertical movements, and hull angular motions.

• *Manual Target Tracking*: The manual target tracking in the simulation code contains four important subroutines, each contributing to the accuracy of the tracking. The reticle to target angles are calculated in one subroutine, while another subroutine is a model of a representative experienced Army gunner. This subroutine simulates the behavior of the gunner as he tracks the target, decides when to issue a laser rangefinder command, and when he begins the firing process. A third subroutine which simulates the fire

control computer performs coordinate transformations of the gunner's handle commands. The last subroutine models the periscope sight and causes the line of sight (LOS) to be held inertial so the gunner can accurately place the reticle on the target.

- *Sight System*: The HIMAG periscope sight, which is a subroutine located within the manual target tracking model, contains four primary components: 1) a stabilized mirror, 2) a laser range finder, 3) the day sight optics, and 4) a thermal sight. By removing all vehicle pitch and yaw movements, the two-axis mirror stabilizes the gunner's LOS. The laser range finder obtains target ranges between 200 m and 5,000 m, and the day optic sights, which have three magnifications, serve as the primary viewing system. Finally, the thermal sight contains infrared and far infrared sensors; these images can be viewed on the binocular eyepiece or on the video monitors.

- *Weapon Recoil Force*: The main objective of this study was to determine the effects of recoil due to fire from a heavy gun tube placed on the LAV. When the gun fires, the projectile is propelled to the target, the gun tube recoils, and the system is subjected to disruptive forces. These recoil forces and torques were generated using time profiles of specific gun recoil systems. These were computed at the trunnion at the proper time in the firing sequence.

3. SIMULATION

The simulation employed was quite flexible; it allowed easy parameter changes and, with the aid of shellscripts, was run in a rather efficient manner. The shellscripts asked for specific scenario conditions, including recoil system, vehicle speed, cant angle, and weapon-to-hull offset. Using this as input, the simulation was run, and the data were collected.

The four vehicle motion/vehicle cant conditions simulated in this study were:

(1) Stationary vehicle at 0° cant
(2) Stationary vehicle at −10° cant
(3) Fire-on-the-move at 0° cant
(4) Fire-on-the-move at −10° cant.

These four scenarios were chosen because they were probable scenarios in real world cases. The four conditions listed were both realistic and properly suited for the simulation.

The fire-on-the-move scenarios were conducted over simulated Terrain 101 (Figure 2), a medium severity terrain with a root mean square value of 1.5 in (altitude). This microterrain profile was produced using data points of surveyed terrain profiles located at Aberdeen Proving Ground. All fire-on-the-move vehicles in this study had a velocity of 20 mph.

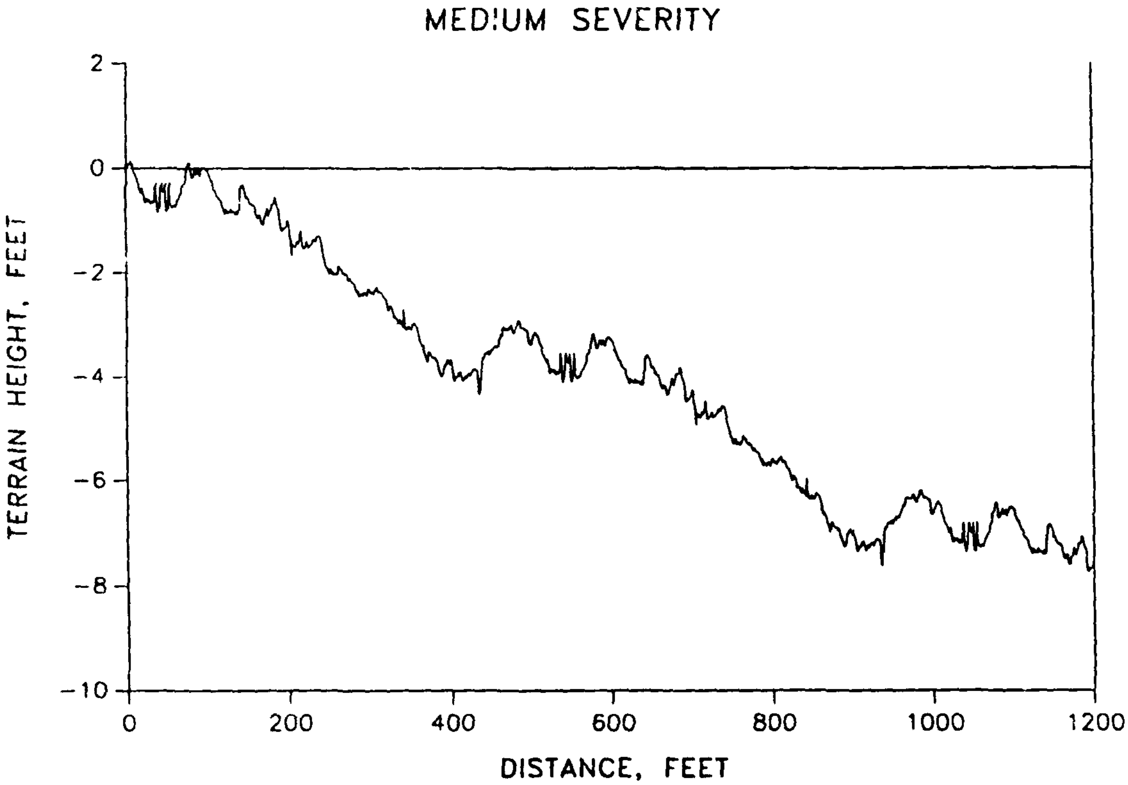

Figure 2. Terrain 101.

The stationary simulation scenarios did not necessarily mean the vehicle was located on a flat surface. For stationary, $-10°$ cant cases, the vehicle was maneuvered onto the canted Terrain 101 profile for a few seconds and then stopped. This enabled the vehicle to achieve the necessary canted condition, while maintaining its stationary condition during the firing process.

As mentioned earlier, the cant angle was achieved through altering the terrain below the vehicle. Negative cant angles and positive target offsets were considered worst-case scenarios.

The four vehicle motion/vehicle cant conditions listed were then subjected to further variations. Specifically, three recoil systems, four different target-to-hull offsets, and a firing/nonfiring state were considered.

Three different recoil systems were analyzed in this study. The Rheinmetall recoil system produced a relatively low force and short recoil distance; thus, its torque reflected a very efficient system. The Rheinmetall will often be referred to as the Low Recoil System—or R105—throughout this report. The second recoil system used was the M68—or Standard 105 Recoil. It produced a substantially higher recoil force and its time to complete the recoil cycle was almost twice that of the Rheinmetall recoil. As a result, its recoil torque responds quicker than the Rheinmetall recoil system, but it takes a longer time to settle (or reach equilibrium). The third recoil system analyzed in this study was the Benet Super Long Recoil System—or SLR105. The SLR105's initial recoil force was slightly higher than the Rheinmetall recoil system, and its recoil distance was over twice that of the other two systems. As a result, the SLR105 torque reflects these differences, and, in turn, produces a much different recoil response. Force, distance, and torque are compared for the three systems in Figures 3, 4, and 5.

Four different target-to-hull offsets were used to adequately represent possible target offsets. When viewing the vehicle from the rear, the 0° target offset placed the gun over the front of the hull. The 30° offset moved the gun tube 30° to the right, the 60° offset moved the gun an additional 30° to the right, and finally, the 90° offset placed the gun over the right side of the vehicle.

Both firing and nonfiring cases were considered. The nonfiring case served as the basis for comparison to the firing case. Similar data from the firing and nonfiring cases were subtracted to obtain hull roll and hull pitch angles due solely to recoil. It was these data that furnished the major results and conclusions from this study.

The complete test matrix (Figure 6) therefore contained a total of 96 runs. For each simulated run, the hull roll and hull pitch angles were analyzed. These particular statistics consumed the majority of the analysis. The test matrix in table form is provided for easy clarification.

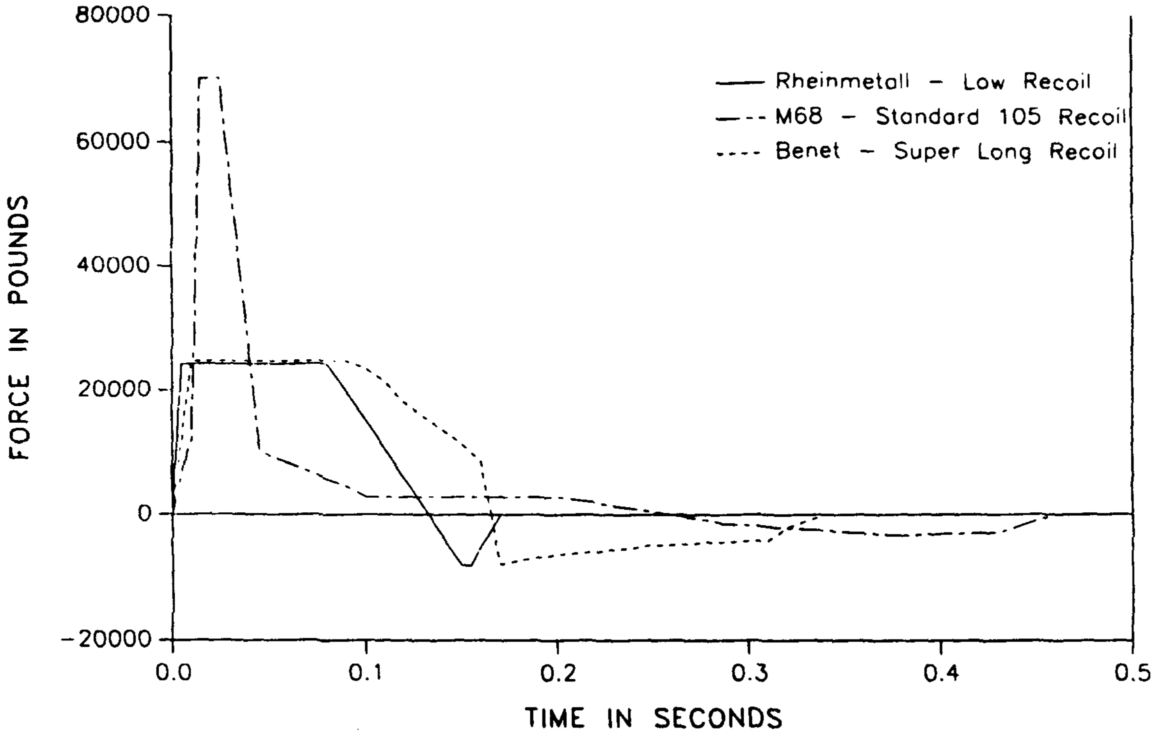

Figure 3. Recoil force.

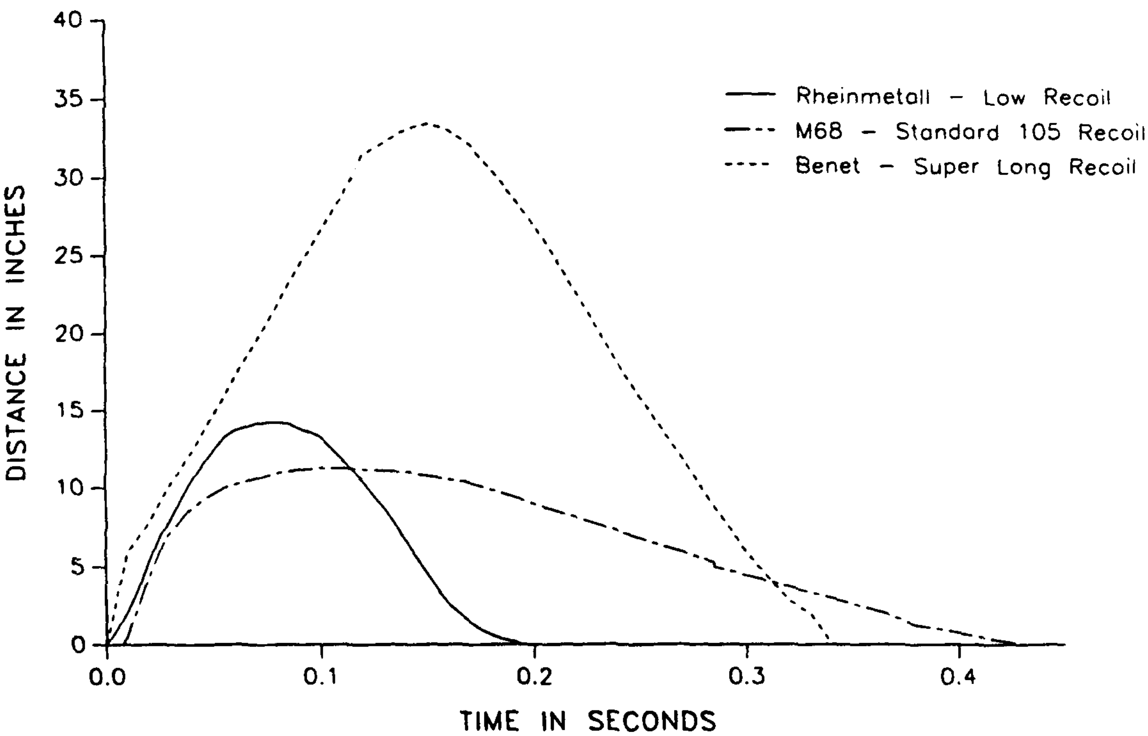

Figure 4. Recoil distance.

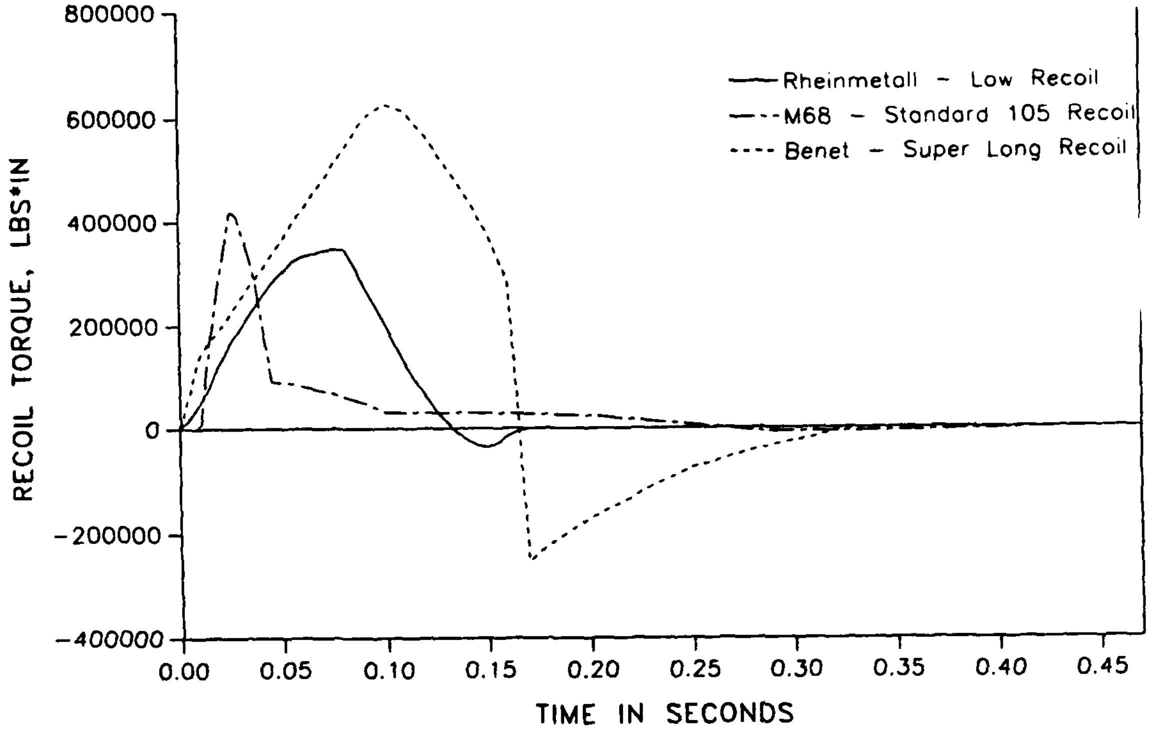

Figure 5. Recoil torque.

TEST MATRIX

VEHICLE MOTION	CANT ANGLE (DEGREES)	RECOIL SYSTEM	TARGET OFFSET (DEGREES)	MODE
STATIONARY	0	RHEINMETALL	0, 30, 60, 90	FIRE / NO-FIRE
		STANDARD	0, 30, 60, 90	FIRE / NO FIRE
		BENET	0, 30, 60, 90	FIRE / NO-FIRE
	-10	RHEINMETALL	0, 30, 60, 90	FIRE / NO-FIRE
		STANDARD	0, 30, 60, 90	FIRE / NO FIRE
		BENET	0, 30, 60, 90	FIRE / NO-FIRE
FIRE ON THE MOVE	0	RHEINMETALL	0, 30, 60, 90	FIRE / NO-FIRE
		STANDARD	0, 30, 60, 90	FIRE / NO FIRE
		BENET	0, 30, 60, 90	FIRE / NO-FIRE
	-10	RHEINMETALL	0, 30, 60, 90	FIRE / NO-FIRE
		STANDARD	0, 30, 60, 90	FIRE / NO FIRE
		BENET	0, 30, 60, 90	FIRE / NO-FIRE

Figure 6. Test matrix.

4. ANALYSIS

There were four plots generated from each scenario run—two for hull roll angles and two for hull pitch angles. The first hull roll angle chart was a two-signal plot containing hull roll motion during the recoil cycle in the firing mode and the hull roll motion during the nonfiring mode. This plot included vehicle cant data (if applicable), the effects due to recoil, and any terrain data that may have been employed in that specific simulation run. The second plot generated for hull roll was derived by subtracting the nonfiring hull roll angle from the firing hull roll angle. This plot, therefore, contained hull roll motion solely due to recoil.

Similarly, there were two charts generated to view pitch angle. The first hull pitch angle chart was a two-signal plot containing hull pitch motion during the recoil cycle in the firing mode and the hull pitch motion during the nonfiring mode. Just as with the hull roll plot, this hull pitch plot included vehicle cant data, the effects due to recoil, and any terrain data (if applicable) that may have been employed in that specific simulation run. The second hull pitch plot generated was derived by subtracting the nonfiring hull pitch angle from the firing hull pitch angle. As a result, this plot contained hull pitch motion solely due to recoil.

The major concern of the analysis was the magnitude of the hull roll angle rather than the magnitude of the hull pitch angle. It was understood that any significant disturbance to the system attributable to firing would occur in the roll direction rather than the pitch direction. This is due to the vehicle's basic design and center of gravity location. The higher disturbance angles occurred in the hull roll signal, regardless of the weapon-to-target offset. Although a full analysis was performed on the hull pitch as well, the concentration of the analysis was the hull roll angles.

4.1 Benign Scenario. Figure 7 shows the hull roll motion created during a recoil cycle for a stationary vehicle at 0° cant with a 30° target offset. This particular plot contains data generated from the Rheinmetall (R105) recoil data. The firing case is represented by the solid line, while the dashed line, barely seen at 10 s and 16 s, represents the nonfiring case in which the weapon system is not disturbed. The solid line actually overlays the dashed line throughout the run, except at the time of fire. At the time of fire, the dashed line remains constant since it represents the nonfiring case. In Figure 7, motion of the vehicle and terrain data were not included (due to the stationary condition), so one can barely see the disturbance in the hull roll angle in the nonfiring case.

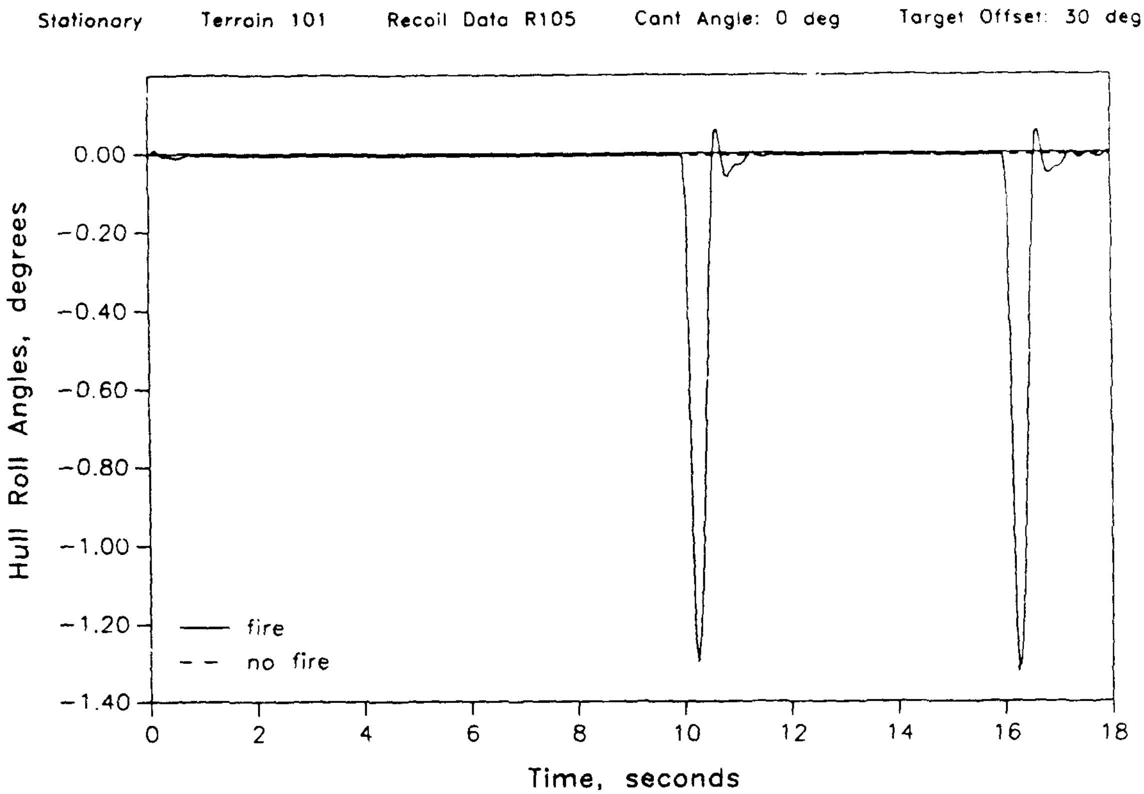

Figure 7. Comparison of stationary roll angles.

The same benign scenario shown in Figure 7 was used to generate Figure 8. This plot was generated by subtracting the nonfiring hull roll angle from the firing hull roll angle. One can see that at the time of fire, the hull roll angle is approximately −1.3°. Regardless of the recoil system used in this particular scenario, firing of the weapon created little disturbance in the hull roll motion.

4.2 Severe Scenario. As stated earlier, the hull pitch angles did not create a large disturbance on the system. The scenario shown in Figure 9 contains data using the SLR105 recoil, a cant angle of −10°, a vehicle traveling 20 mph over Terrain 101 (medium severity), with a target offset of 90°. This was the worst-case scenario for this investigative study. Again, the firing data are shown with a solid line, and the nonfiring data are shown with the dashed line. The overlaying of the firing case on top of the nonfiring case helps reveal the effects due to recoil. Even though the disturbances are relatively small, one can see that the majority of the pitch disturbances occur because of the terrain and are not due to firing. This can be seen by viewing the dashed lines at 10, 16, and 22.5 s (time of firings). The highest value of the hull pitch angle is approximately 4.0°, and that is not due to the recoil effects.

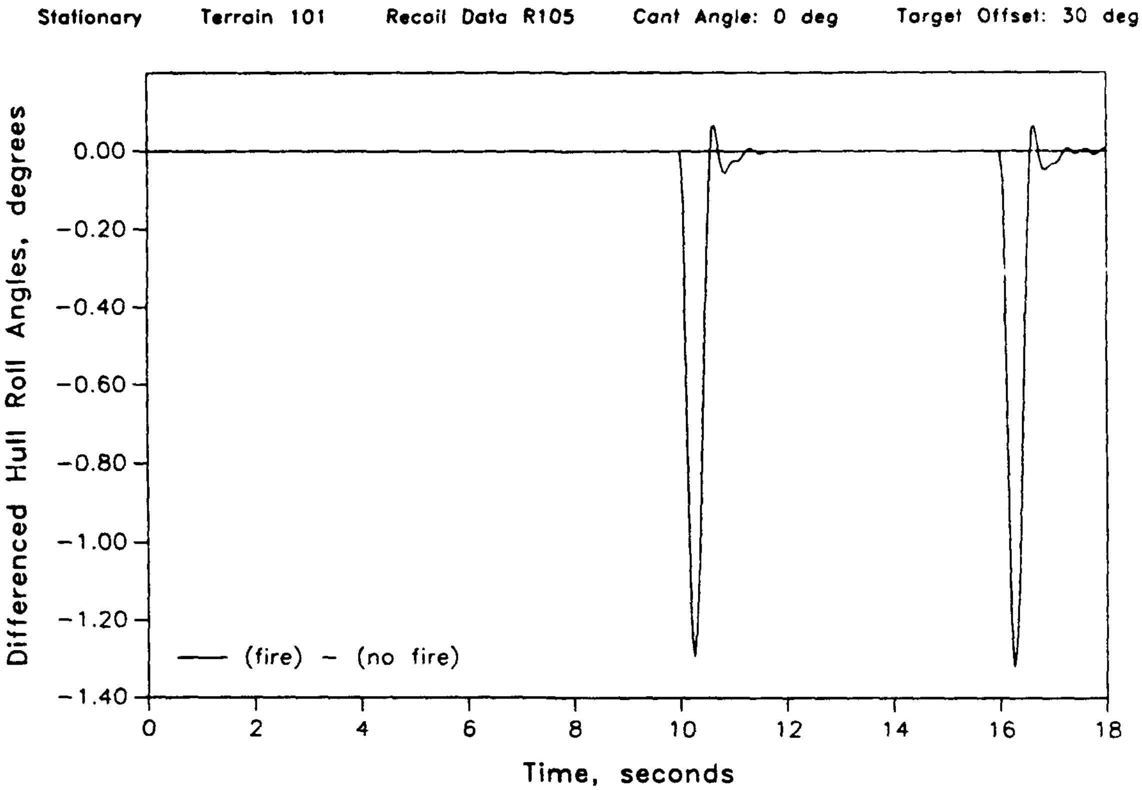

Figure 8. Differenced stationary roll angles.

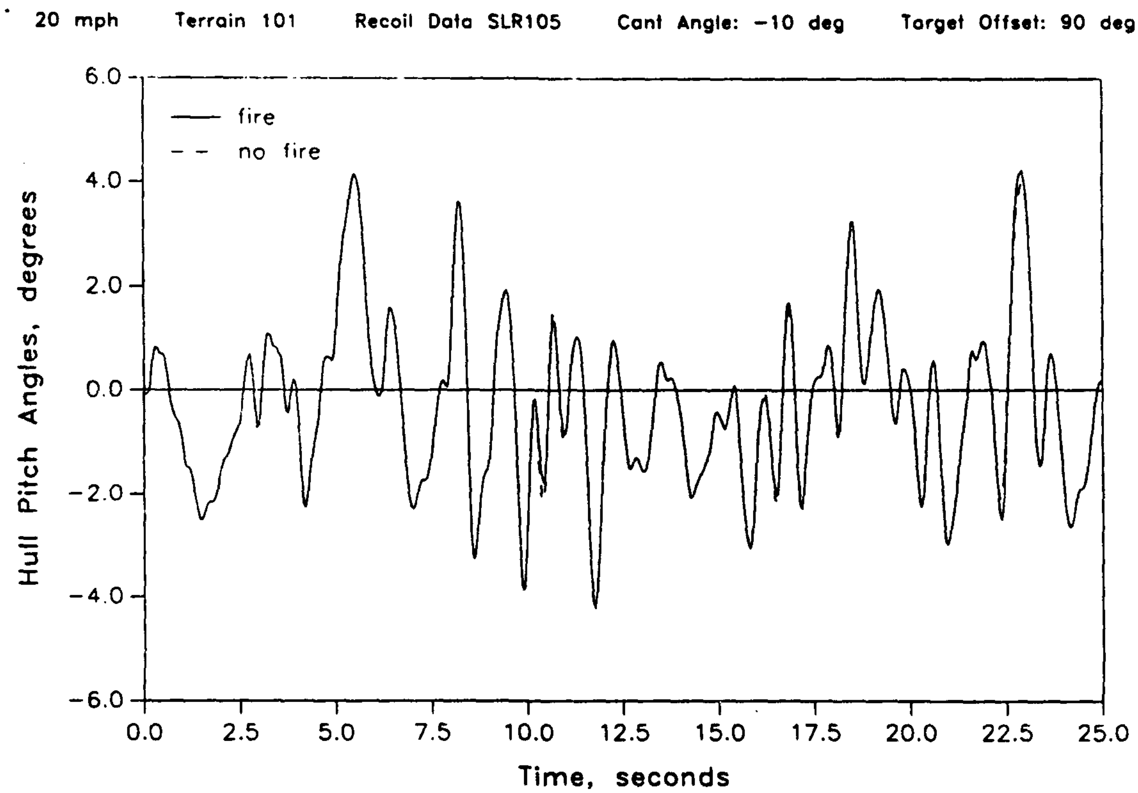

Figure 9. Comparison of moving pitch angles.

By subtracting the two signals in Figure 9, we can exactly see the disturbance put on the system due only to recoil. The pitch chart shown in Figure 10 reveals that the greatest stress on the hull pitch motion due solely to recoil is approximately –0.50°. Regardless of the recoil system employed, the hull pitch angle due solely to recoil was minimal.

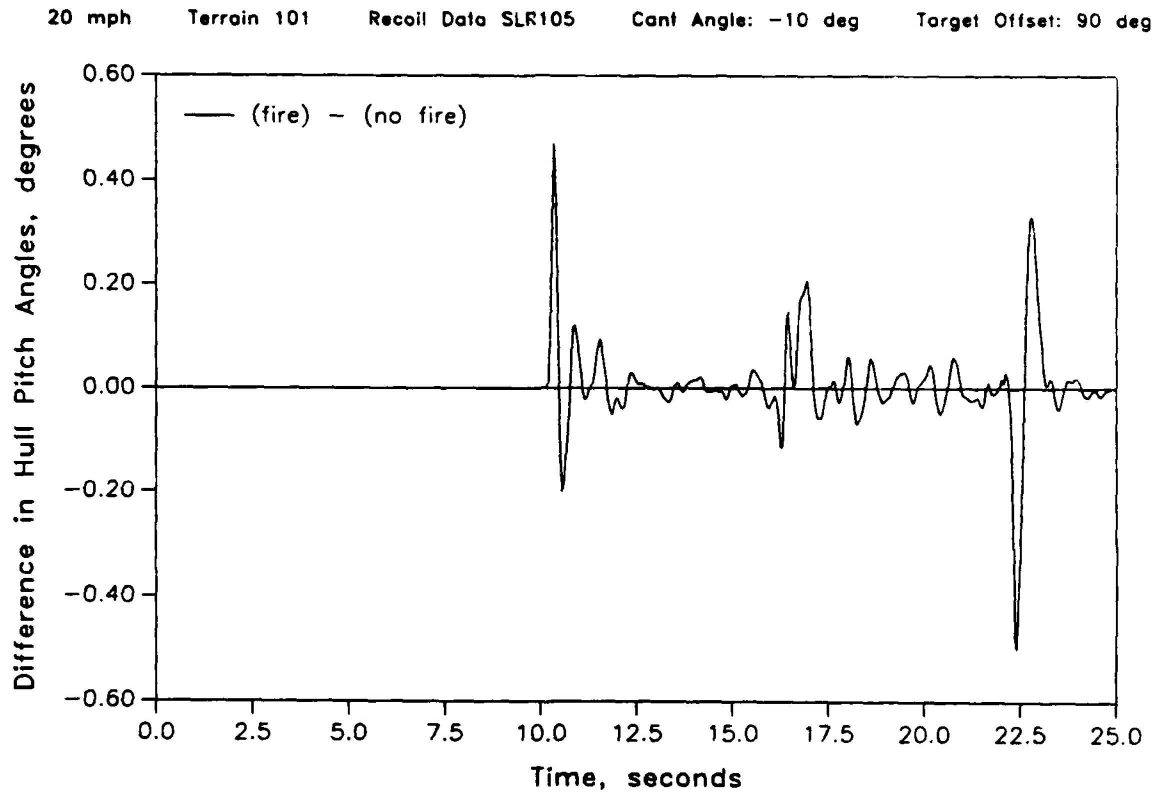

Figure 10. Differenced moving pitch angles.

Figure 11 shows the stress the hull roll angle encountered during the same scenario described earlier. The time of fire is easily discerned by the three spikes seen on the plot. The first 2 s of the run contain a rapid change in roll angle as a result of the vehicle approaching the desired cant angle of –10°. As explained earlier, this is due to the time required for the vehicle to get positioned onto the canted terrain. The greatest roll angle seen in this run (approximately –15.5°) occurs at the first shot. This value includes the canted terrain data, along with the recoil disturbance. We can obtain a greater understanding of the disturbance due only to firing by looking at Figure 12. This chart shows the difference on the firing hull roll signal and the nonfiring hull roll signal. We can see that the greatest additional disturbance was encountered at the first shot. The recoil of the Super Long Recoil System produced an additional –4.0°

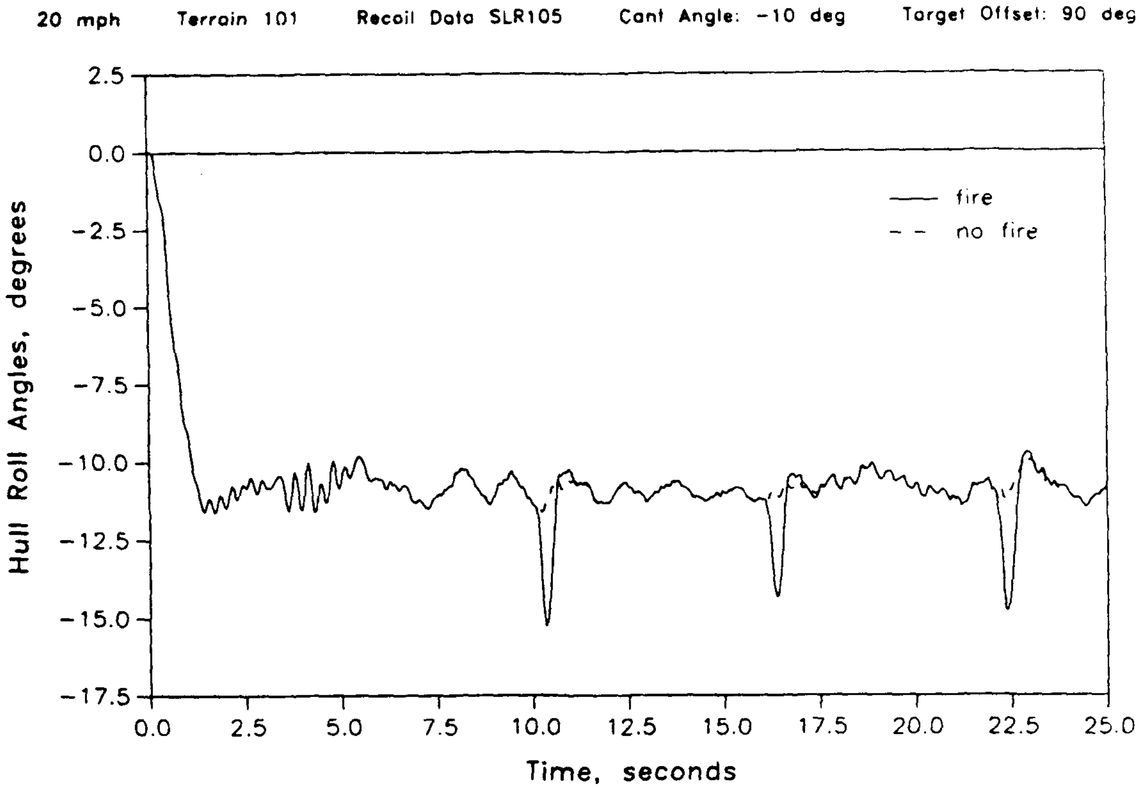

Figure 11. Comparison of moving roll angles.

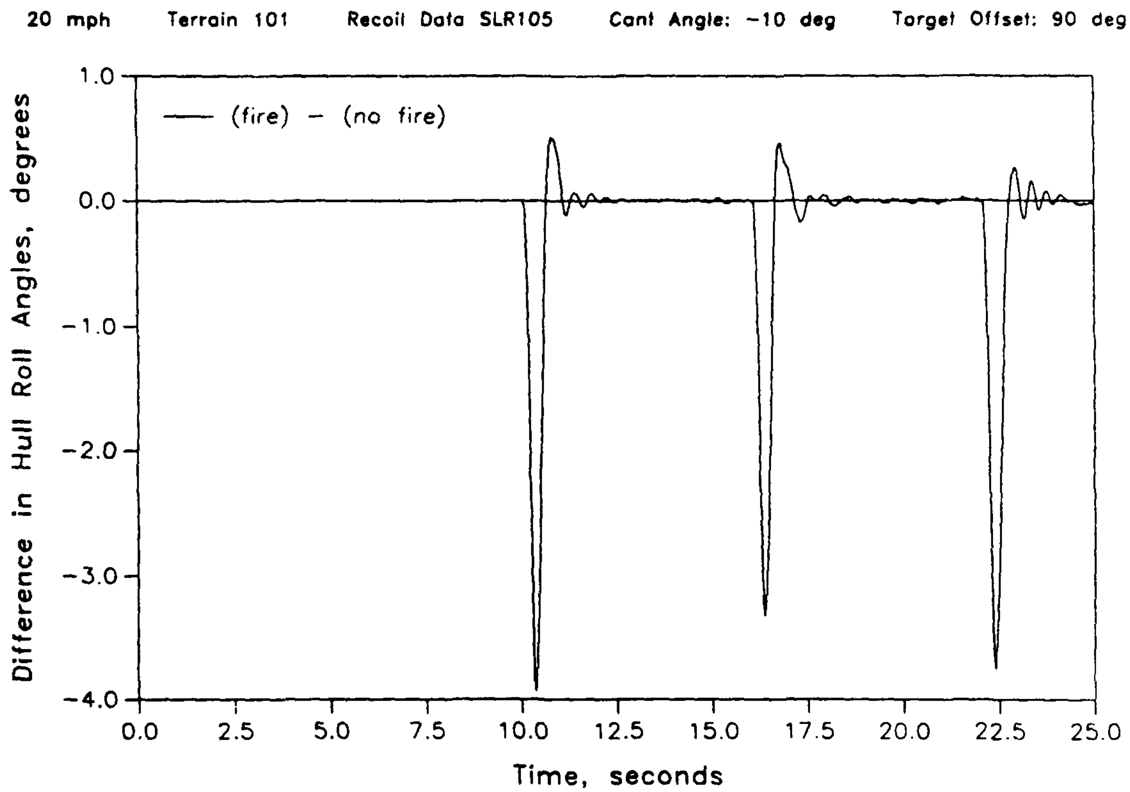

Figure 12. Differenced moving roll angles.

on the system. This, coupled with the initial −10° cant and specific terrain disturbance occurring at the time of fire, taxed the system for a total of approximately −15°.

4.3 Bar Chart Descriptions. Sixteen bar charts have been created to summarize all the various data collected in this study. As mentioned earlier, there were four vehicle motion/vehicle cant conditions simulated in this study:

(1) Stationary vehicle at 0° cant
(2) Stationary vehicle at −10° cant
(3) Fire-on-the-move at 0° cant
(4) Fire-on-the-move at −10° cant.

For each of these four scenarios, four summary bar charts were created containing the highest value (disturbance) that the system encountered during the run. All three recoil systems used in the study are shown for easy comparison. The four summary bar charts simply contain the highest numerical value encountered as collected from the four main scenarios explained above. The four summary bar charts are titled as followed:

(1) 0 to −Peak Hull Roll Angle During Recoil Cycle
(2) 0 to −Peak Hull Roll Motion Due Solely to Recoil
(3) 0 to −Peak Hull Pitch Angle During Recoil Cycle
(4) 0 to −Peak Hull Pitch Motion Due Solely to Recoil.

In addition to these basic titles, scenario specifications are included for each bar chart. All moving vehicles were traveling at 20 mph. The only exception to this format is in the stationary, 0° cant scenario. For these runs, the greatest disturbance occurred in the positive direction for the hull pitch angle; however, these disturbances are very small.

4.3.1 Stationary Vehicle.

• *0° Cant.* The comparative hull roll motion charts obtained from the stationary, 0° cant scenario are found in Figures 13 and 14. As intuitively expected, the higher the weapon-to-hull offset, the greater the disturbance in the hull roll angles. Due to this benign scenario, there were minimal vehicle roll angles occurring, regardless of recoil system or weapon-to-target offset. Note that the M68 - Standard 105 Recoil

system and the Rheinmetall - Low Recoil system handled the disturbances better than the Benet - Super Long Recoil system, regardless of weapon-to-target offset.

Figures 15 and 16 show the hull pitch charts for the stationary 0° cant scenario. Notice the trend that occurs as weapon-to-hull offset increases: as expected, pitch angles decrease due to the movement away from the front of the turret, thus less of a disturbance in the pitch angle. In addition, it can be noted that again the Rheinmetall and the M68 recoil systems handle the disturbances much better than the Benet recoil system.

- *10° Cant.* Figures 17 and 18 show the largest hull roll motions generated during a canting of −10° for a stationary vehicle firing from Terrain 101. In Figure 17, one can see that the greatest disturbance occurs at the 60° and 90° weapon-to-hull offset when using the Benet - Super Long Recoil system. By subtracting out the cant data and other disturbances not involved in firing, we can see from Figure 18 that an additional −3.35° is added to the initial −10° canted vehicle when it fires over the side (90°). The same trend that was observed in Figures 13 and 14 occurs here, that is, the greater the weapon-to-hull offset, the greater the vehicle roll angle.

Figures 19 and 20 display the largest hull pitch angles that occurred during a canting of −10° for a stationary vehicle firing from Terrain 101. There was practically no disturbances brought about by recoil in any of the cases, regardless of weapon-to-hull offset or recoil system used. This is emphasized by seeing Figure 20, which reveals the hull motion nonfiring pitch angle subtracted from the hull motion firing case pitch angle.

4.3.2 Moving Vehicle.

- *0° Cant.* Figures 21 and 22 contain hull roll motion data from the 0° cant, fire-on-the-move scenarios. It can be seen that the same trends occur in the fire-on-the-move-scenarios as in the stationary scenarios: the larger the weapon-to-hull offset, the larger the hull roll angles. The greatest disturbance occurs at the 90° weapon-to-target offset using the Benet - Super Long Recoil System. The greatest angle due solely to recoil is −3.93°. This poses no threat to the vehicle, i.e., overturning.

The greatest disturbances found in the hull pitch angles for the same scenario as in Figures 21 and 22, are shown in Figures 23 and 24. Again, the trends remain consistent: the greater the weapon-to-hull

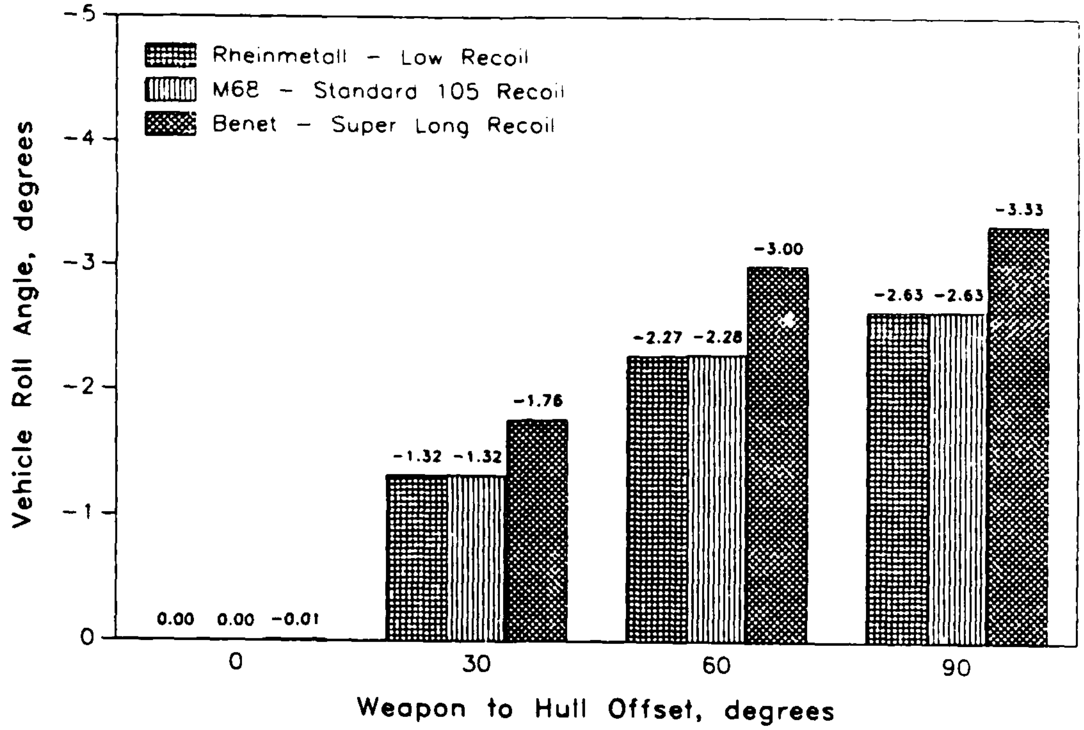

Figure 13. 0 to –peak hull roll angle during recoil cycle (stationary, 0° cant).

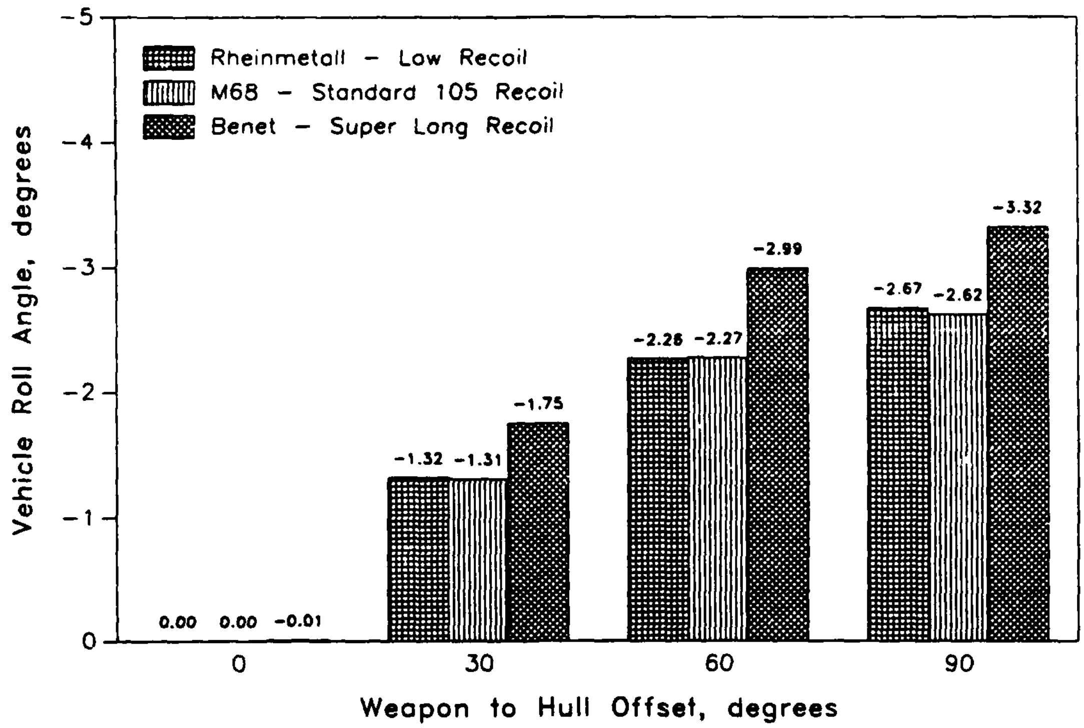

Figure 14. 0 to –peak hull roll motion due solely to recoil (stationary, 0° cant).

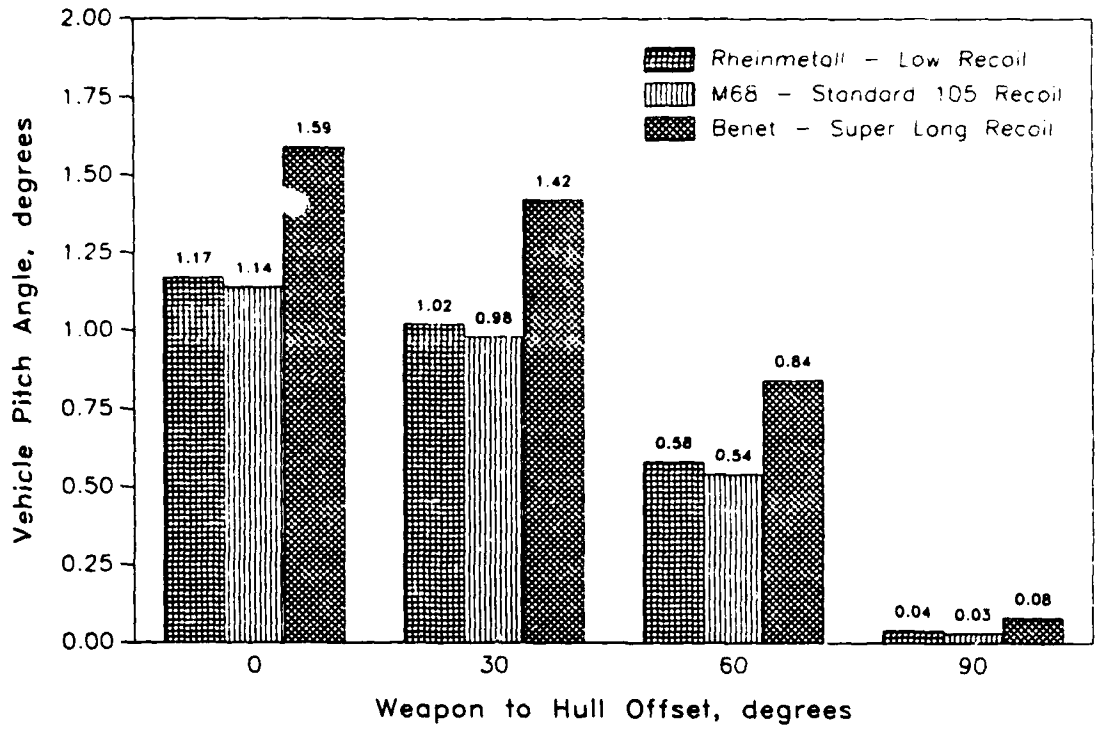

Figure 15. 0 to +peak hull pitch angle during recoil cycle (stationary, 0° cant).

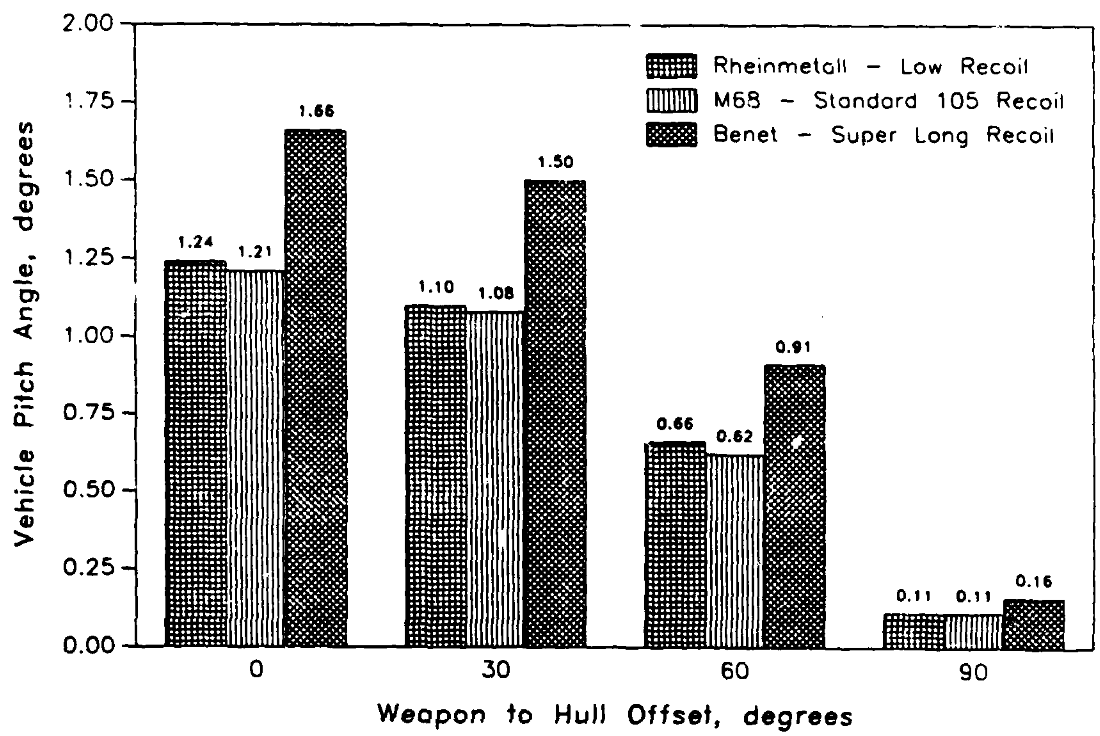

Figure 16. 0 to +peak hull pitch motion due solely to recoil (stationary, 0° cant).

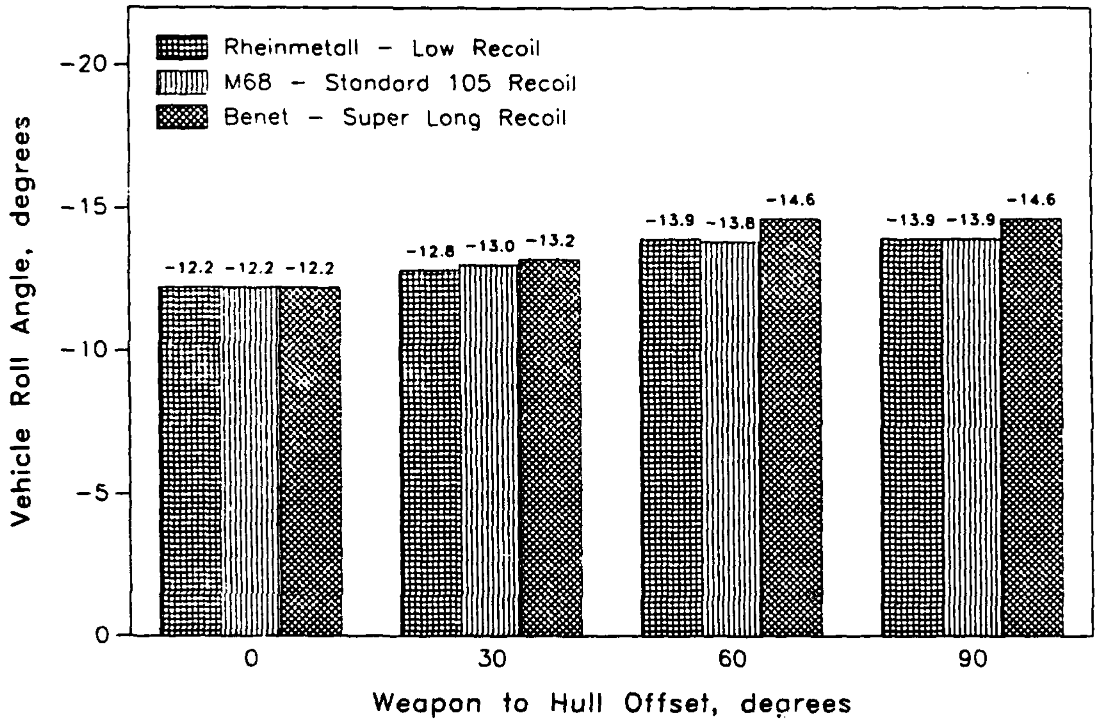

Figure 17. 0 to –peak hull roll angle during recoil cycle (stationary, –10° cant).

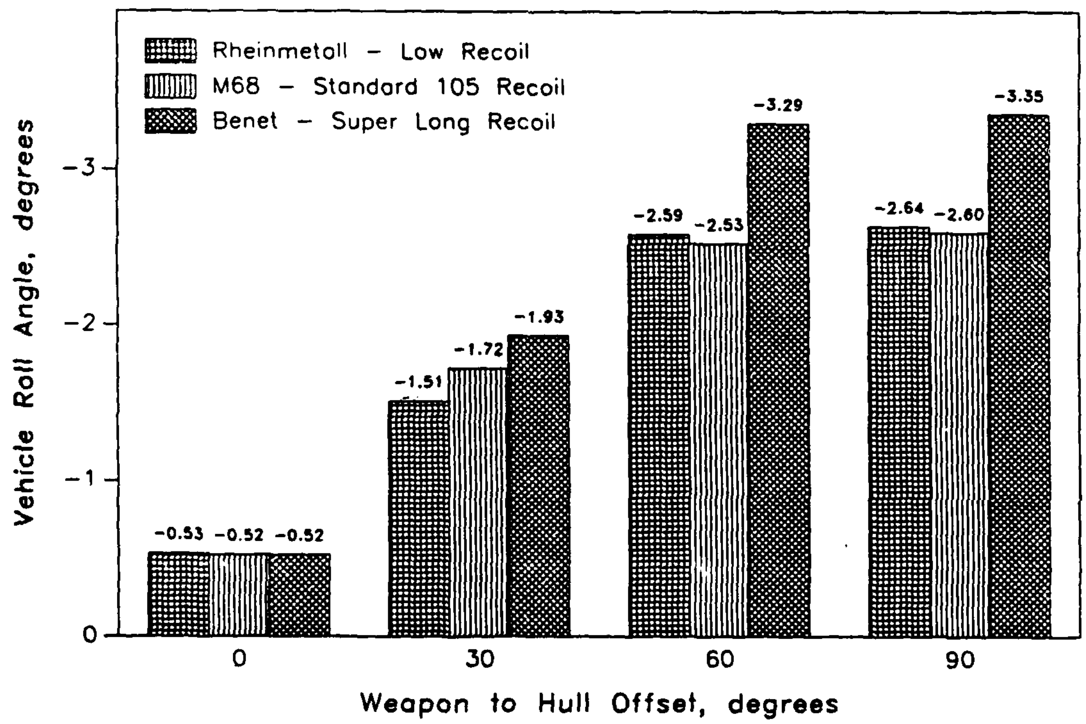

Figure 18. 0 to –peak hull roll motion due solely to recoil (stationary, –10° cant).

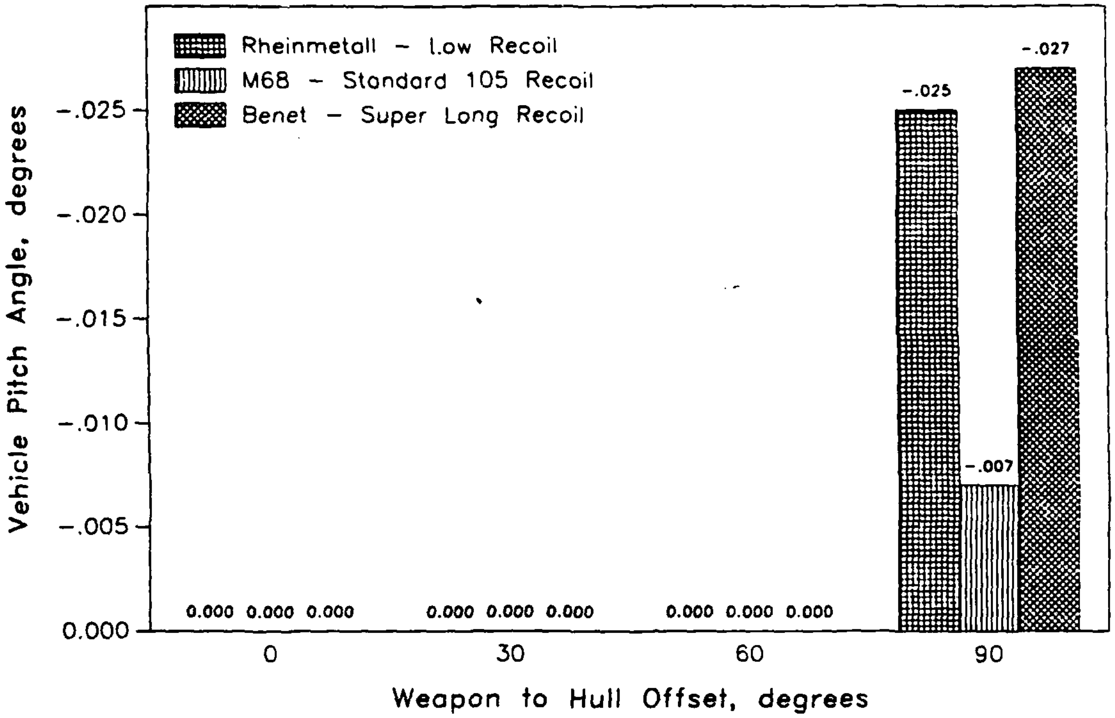

Figure 19. 0 to –peak hull pitch angle during recoil cycle (stationary, –10° cant).

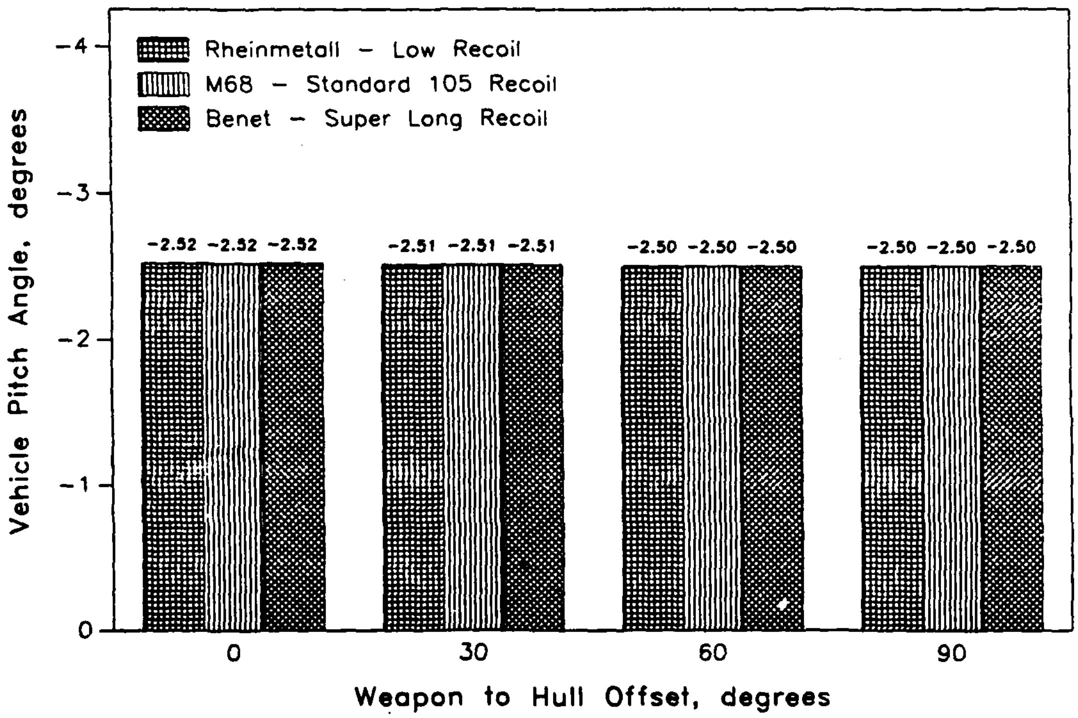

Figure 20. 0 to –peak hull pitch motion due solely to recoil (stationary, –10° cant).

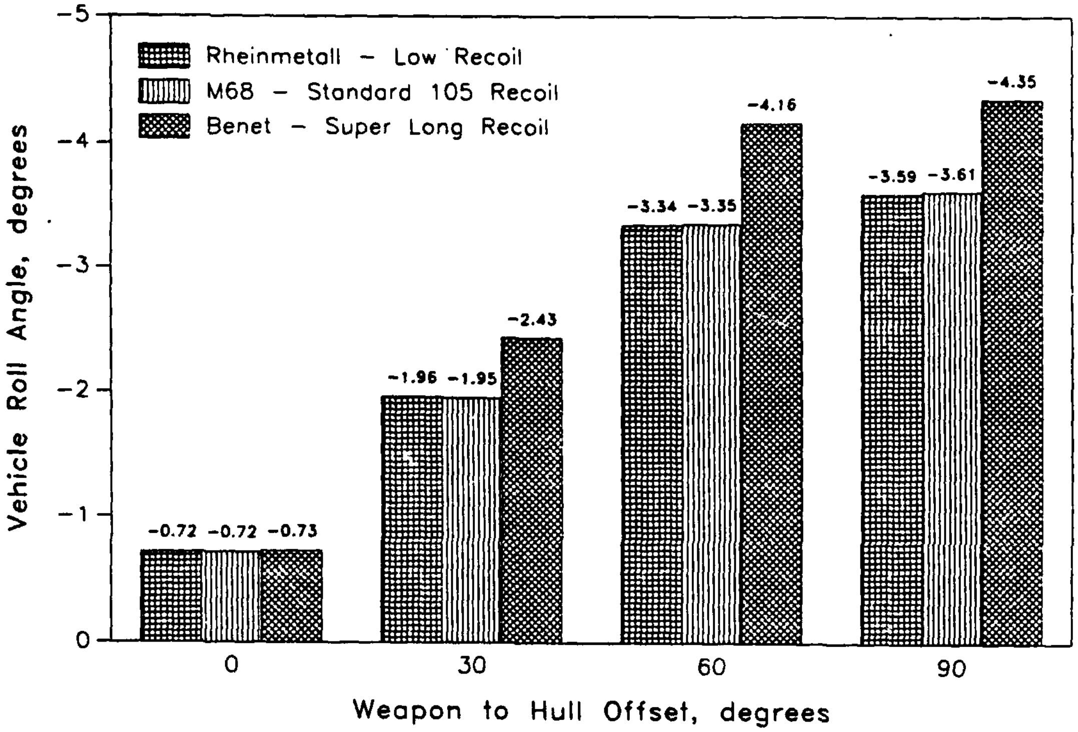

Figure 21. 0 to -peak hull roll angle during recoil cycle (moving, 0° cant).

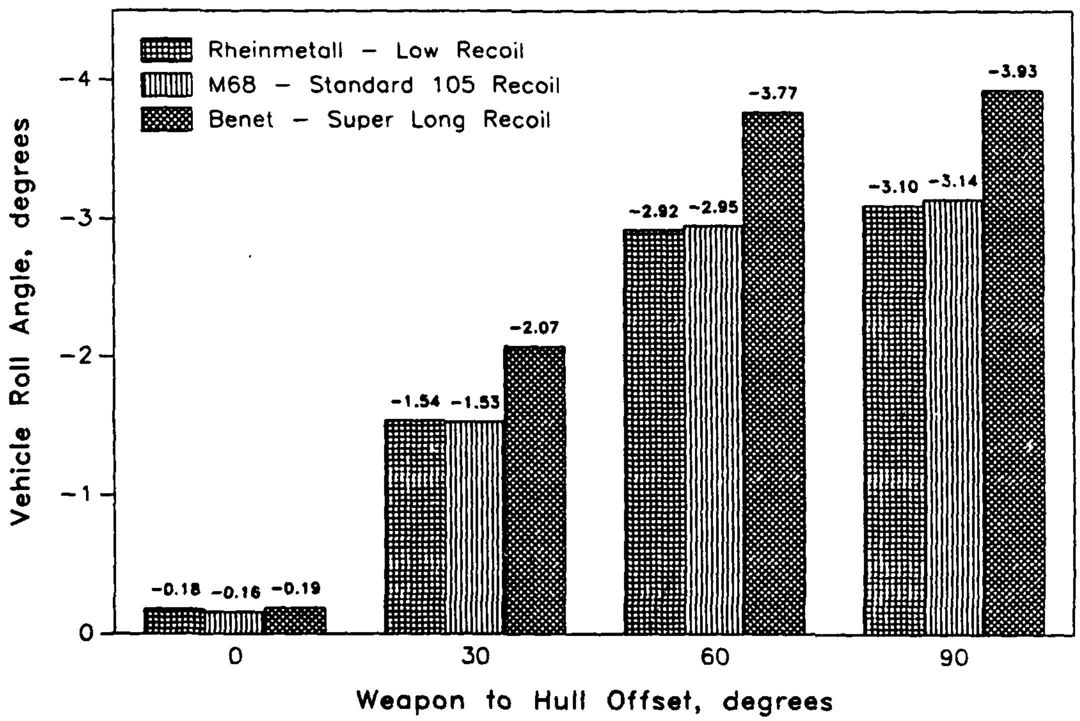

Figure 22. 0 to -peak hull roll motion due solely to recoil (moving, 0° cant).

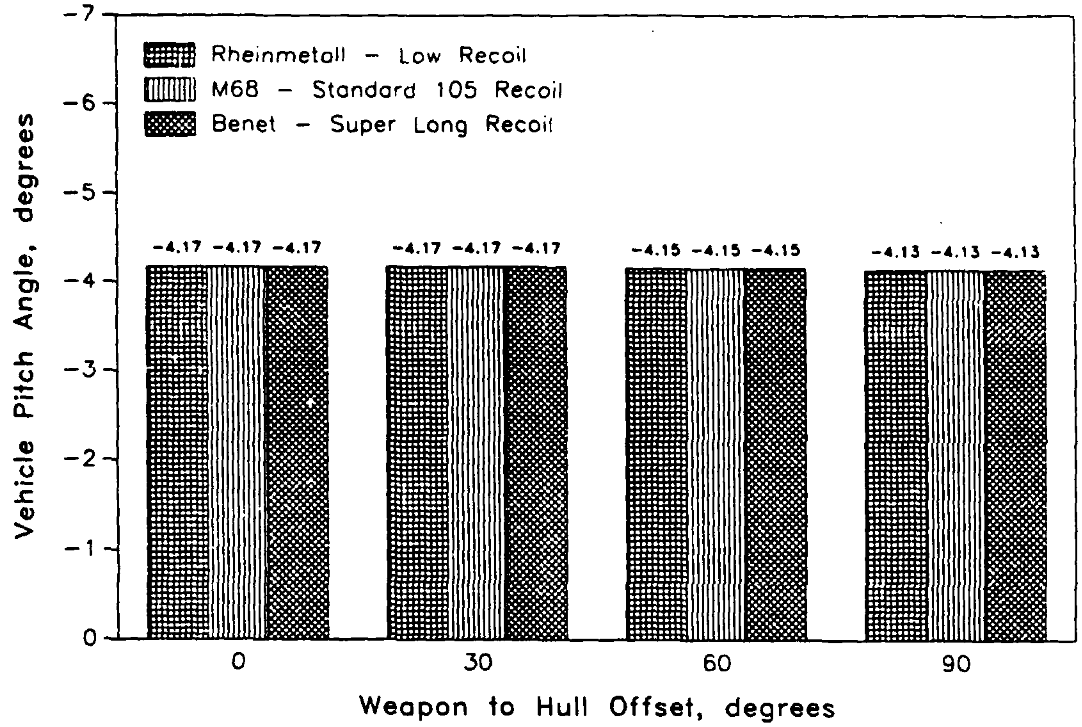

Figure 23. 0 to –peak hull pitch angle during recoil cycle (moving, 0° cant).

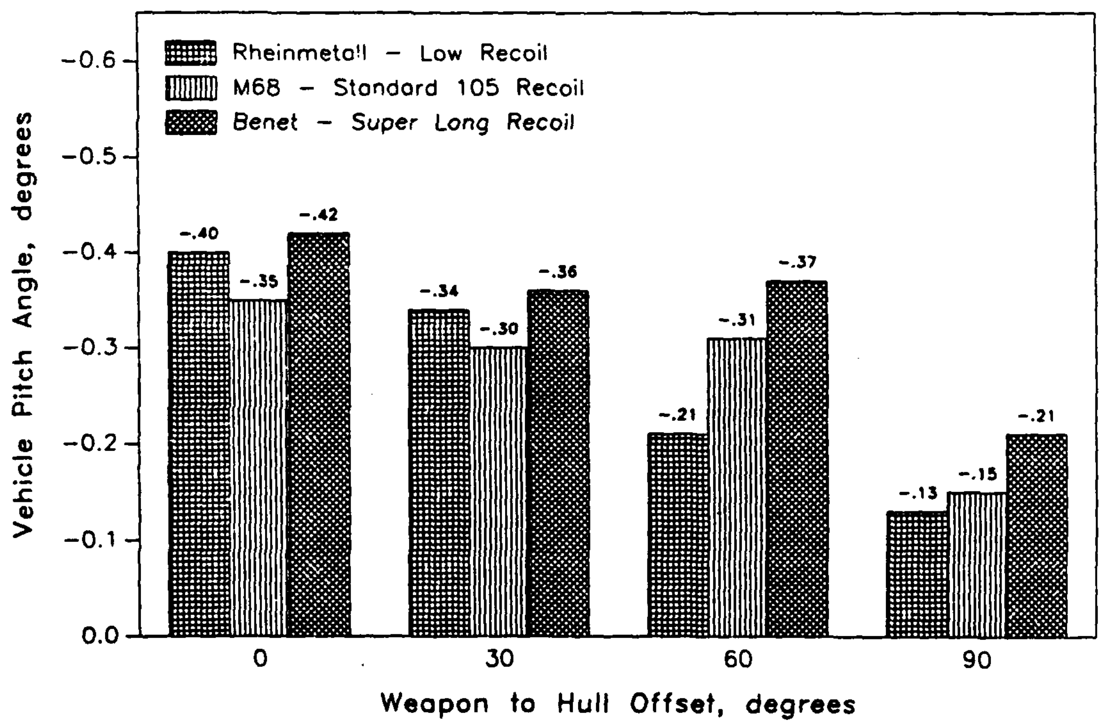

Figure 24. 0 to –peak hull pitch motion due solely to recoil (moving, 0° cant).

offset, the less the hull pitch angles. Even when the terrain data is subtracted out, as shown in Figure 24, there is very little disturbance placed on the system due to firing of the weapon.

- *10° Cant.* Figures 25 and 26 show the largest hull roll angle found in the most severe case of this study: fire-on-the-move at −10° cant. The vehicle traveling 20 mph over medium severity terrain, coupled with the command to fire over the side produced the most significant hull roll angles. Including terrain data, the roll angle was −15.3° while using the Benet - Super Long Recoil system and firing over the side. Figure 26 shows us the disturbance due only to recoil. We can observe that the greatest value is approximately −4°.

The largest hull pitch angles generated from the same scenario described in Figures 25 and 26 reveal no threat to the vehicle overturning. Figure 27 shows us the total pitch angle that occurred in the system; this reveals that the greatest disturbance is −4.25°. Once the terrain data is subtracted, the pitch angles due solely to recoil are obviously still small. We can view this in Figure 28; the greatest value of −0.90° is found in the 0° weapon-to-hull offset when the Benet - Super Long Recoil system was employed.

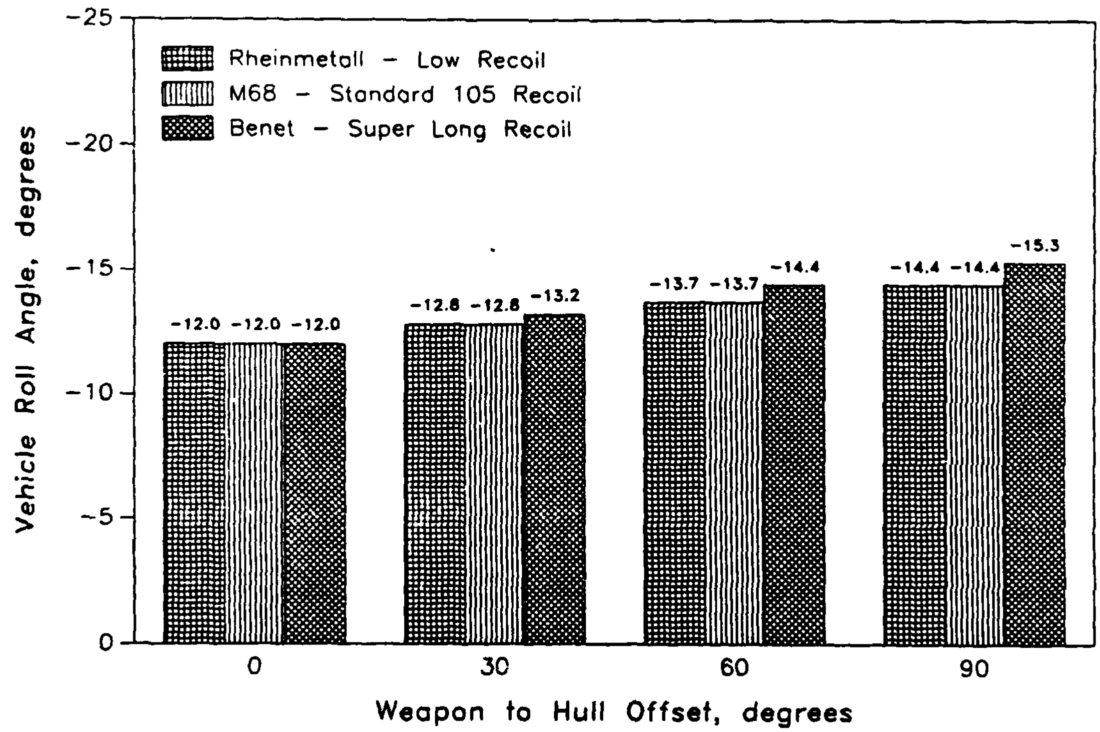

Figure 25. 0 to −peak hull roll angle during recoil cycle (moving, −10° cant).

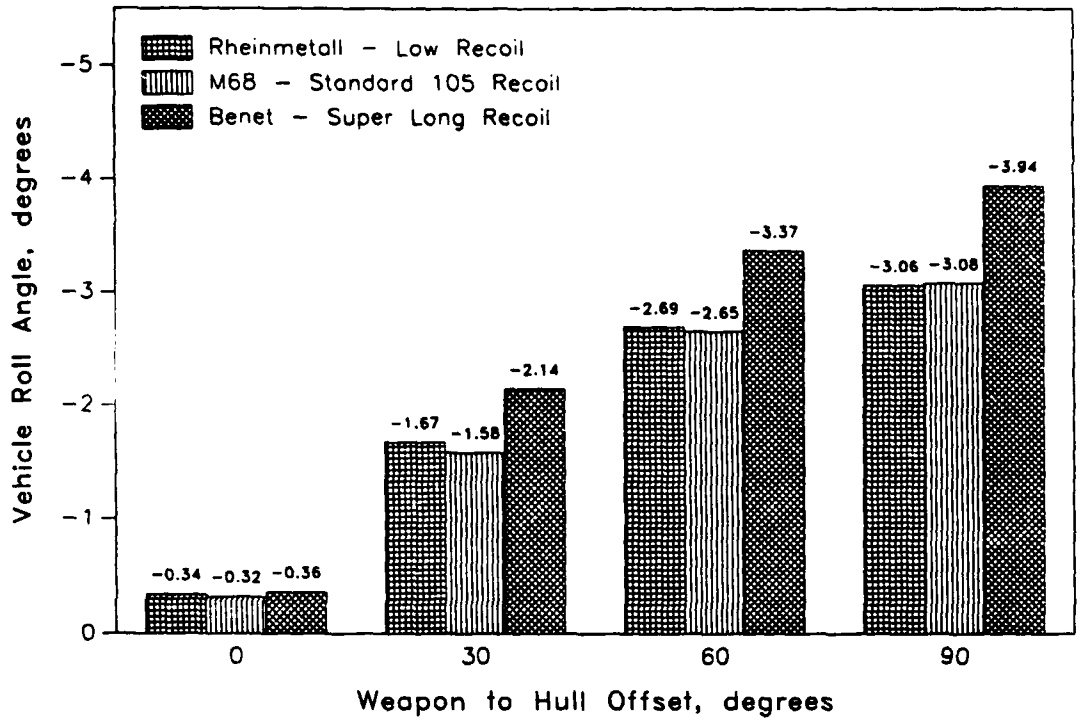

Figure 26. <u>0 to –peak hull roll motion due solely to recoil (moving, –10° cant).</u>

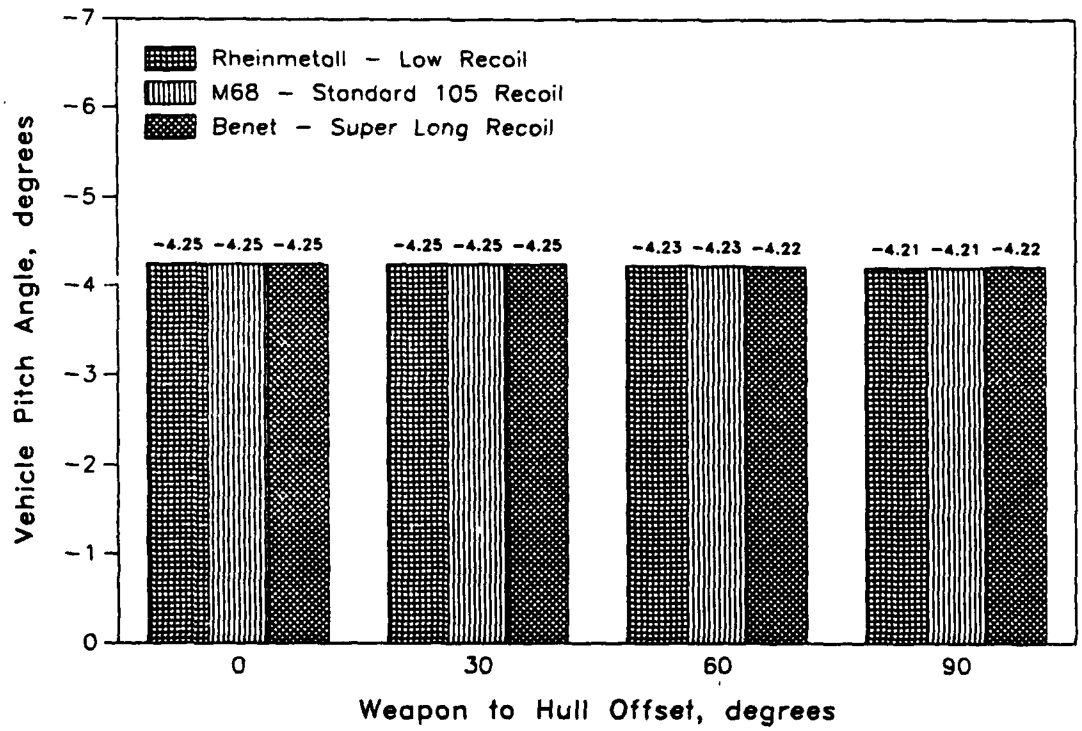

Figure 27. <u>0 to –peak hull pitch angle during recoil cycle (moving, –10° cant).</u>

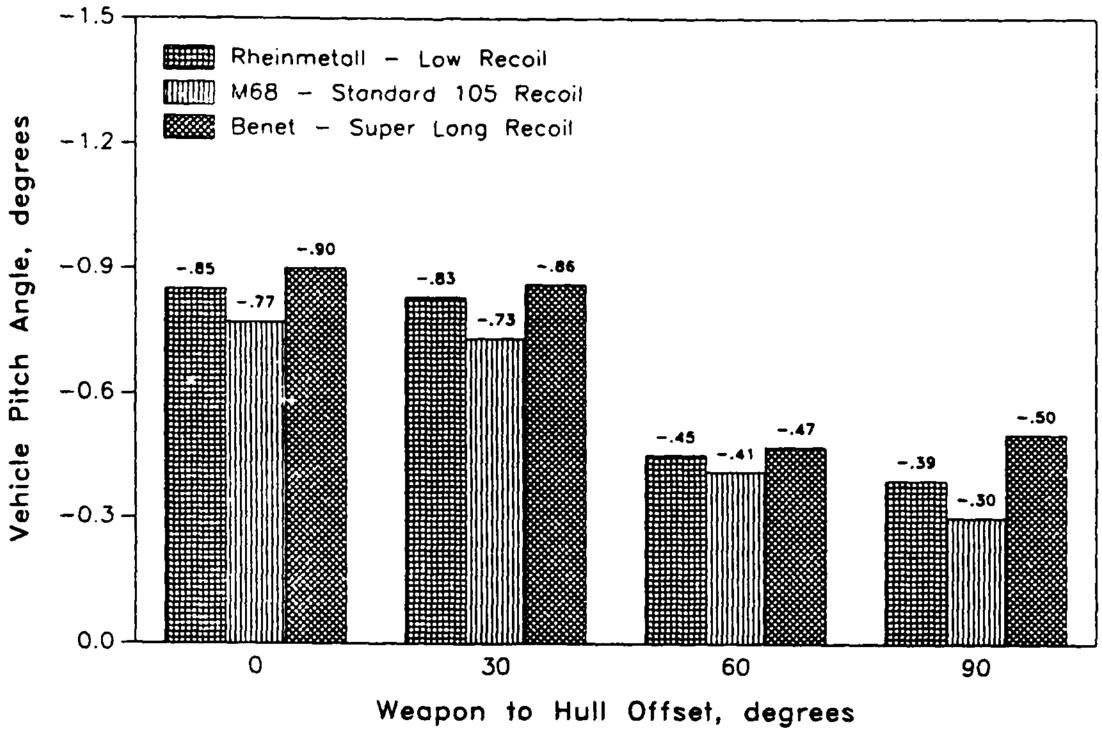

Figure 28. 0 to −peak hull motion due solely to recoil (moving, −10° cant).

5. SUMMARY

Weapon recoil effects on the USMC LAV have been studied under a variety of conditions using three different recoil systems. The largest hull roll angle due solely to recoil, −3.94°, occurred when the scenario employed the Benet - Super Long Recoil, a medium severity terrain, vehicle speed of 20 mph, and a shot fired over the side of a vehicle canted −10°. The largest hull pitch angle due to recoil, 1.66°, occurred when the scenario employed the Benet-Super Long Recoil, a weapon-to-target offset of 0°, and a stationary vehicle with 0° cant. Neither of these angles is severe enough to cause the LAV to overturn.[3]

Of the three systems tested, the Benet - Super Long Recoil system had the worst performance. The other two systems performed about the same, but with a slight advantage to the M68 - Standard 105 Recoil system.

[3] Dick Norman from AMSAA estimated an angle of 40° or more as the overturning angle of the LAV-105 vehicle.

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